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MATERIALS PROCESSING

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NONDESTRUCTIVE METHODS IN LASER TREATMENT OF GLASS AND CERAMIC PLATES

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One-sided heating of a plate freely fixed along its contour by a volume source is considered in the context of a quasistatical disjoint thermoelasticity problem. An analytical relationship is obtained, which is the criterion of the thermal strength of the plate, making it possible to identify nondestructive laser treatment regimes, as well as the thermal strength of existing and newly developed materials. An experimental verification of the adequacy of the proposed model is performed.

The methods for treating optical glass, ceramics, and semiconductor materials include, along with traditional high-temperature annealing, the irradiation of their surfaces using continuous or pulse laser radiation [1 – 3]. Fast heating of a plate by laser radiation and its slow cooling relax the residual stresses which arise in the surface layer under polishing [3]. However, the materials treated can be partly permeable for radiation. In heating a plate certain treatment parameters may emerge under which thermoelastic stresses become prevalent in the technological process. To prevent the bending of the plate, it is usually freely fixed along its contour. In order to determine nondestructive treatment regimes, let us consider the solution to a disjoint quasistatic problem of thermal elasticity for this plate. We assume the thermophysical and mechanical properties of the plate to be independent of temperature. We will regard the plate as heat-resistant if it is not destroyed by thermoelastic stresses, as its surface is heated to the melting point.

Let us assume that the flux density is uniformly distributed across the laser beam, is constant in time, and decreases across the plate thickness in accordance with Bouguer's law. Neglecting the radiation losses on the plate surface and assuming the properties of the material of the plate to be independent of temperature, it is possible to find the temperature field in this plate by the Fourier integral transform method [4]. For a constant flux density of laser radiation the temperature field in the plate is calculated from the relation

$$T(\xi, t) = T_0 + \frac{A_\Psi W \Theta(\xi, \bar{t})}{c\gamma h}, \tag{1}$$

where $T(\xi, t)$ is the temperature; $\xi = z/h$ is the dimensionless coordinate (z is the coordinate across the plate thickness; h is the plate thickness); t is the time of exposure to the radiation effect; T_0 is the initial temperature; $A_\Psi = (1 - R)(1 - e^{-\chi h})$ is the absorption coefficient (R is the reflection coefficient; χ is the absorption index of the material of the place for the radiation wavelength); $W = q_0 t$ is the energy density; c and γ are the specific heat and density of the material of the plate, respectively (q_0 is the density of the laser flux upon the plate surface); $\Theta(\xi, \bar{t})$ is the dimensionless excess temperature found from the equation

$$\Theta(\xi, \bar{t}) = \bar{t} + \frac{2}{\mathrm{Fo}(1 - e^{-\chi h})} \sum_{n=1}^{\infty} \frac{[1 - (-1)^n e^{-\chi h}]}{\left[1 + \frac{\pi^2 n^2}{(\chi h)^2}\right] \pi^2 n^2} \times$$
$$[1 - e^{-\pi^2 n^2 \mathrm{Fo}\, \bar{t}}] \cos(\pi n \xi), \tag{2}$$

where $\bar{t}$ is the dimensionless time (for constant flux density $\bar{t} = 1$ [4]); $\mathrm{Fo} = at/h^2$ is the Fourier number (a is the thermal conductivity of the plate material); $n = 1, 2, 3, ..., \infty$ is an integer number.

The dimensionless excess temperature is the ratio of the temperature to the average limiting excess temperature $T(\xi, \bar{t})/T_\Psi^*$ [4]. The average limiting excess temperature is set after the end of heating and adiabatic leveling of temperature. It is calculated from the following formula [4]:

$$T_\Psi^* = \frac{A_\Psi W}{c\gamma h}.$$

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Thermoelastic stresses arise in the plate freely fixed under the effect of the temperature field [5]:

$$\sigma_x(z,t)=\sigma_y(z,t)=\frac{E}{1-\nu}\{\varepsilon_T-\alpha_T[T(z,t)-T_0]\};\quad (3)$$

$$\varepsilon_T=\frac{1}{h}\int_0^h \alpha_T[T(z,t)-T_0]\mathrm{d}z,\quad (4)$$

where E is the Young modulus; ν is the Poisson coefficient; α_T is the average TCLE of the plate for the temperature interval.

An earlier analysis [6, 7] indicated that the maximum tensile stresses arise in the plate section ($\xi = 1$) where the temperature is minimal. By substituting expression (1) taking into account formula (2) into Eqs. (3) and (4) and performing mathematical transforms we will obtain an equation for the calculation of the energy density leading to destruction of the plate by thermoelastic stresses:

$$W_T=\frac{\sigma_r(1-\nu)c\gamma h}{E\alpha_T A_\Psi[\overline{\Theta}(\bar t)-\Theta(\xi=1,\bar t)]}=\frac{\sigma_r(1-\nu)c\gamma h}{E\alpha_T(1-R)f_T(\chi h,\mathrm{Fo})},\quad (5)$$

where σ_r is the tensile strength of the plate material; $\overline{\Theta}(\bar t)$ is the average dimensionless excess temperature across the plate thickness (at $q_0 = \mathrm{const}$ $\overline{\Theta}(\bar t) = 1$ [4]; $\Theta(\xi = 1, \bar t)$ is the dimensionless excess temperature on the surface ($\xi = 1$), which is calculated from Eq. (2).

Using expression (1) taking into account formula (2), we obtain an equation for the calculation of the energy density required for the surface ($\xi = 0$) to reach the melting point:

$$W_f=\frac{(T_f-T_0)c\gamma h}{A_\Psi\Theta(\xi=0,\bar t)}=\frac{(T_f-T_0)c\gamma h}{(1-R)f_f(\chi h,\mathrm{Fo})},\quad (6)$$

where $\Theta(\xi = 0, \bar t)$ is the dimensionless excess temperature on the surface of the plate, which is calculated from Eq. (2).

By dividing Eq. (5) by formula (6) and assuming the condition $W_T/W_f \geq 1$, we obtain a criterion of the thermal strength of the plate for the volume absorption of laser radiation under a continuous effect:

$$\frac{\sigma_r(1-\nu)}{E\alpha_T(T_f-T_0)}\geq f(\chi h,\mathrm{Fo}).\quad (7)$$

Thus, an analytical relationship is derived, which is the criterion of the thermal strength of a plate freely fixed along its contour under one-sided heating from a volume source; this criterion decreases along the plate thickness in accordance with Bouguer's law. The model proposed is valid for the absorption indexes of plate materials with laser radiation wavelength over 0.1 cm^{-1}, when it is possible to neglect such mechanisms of the destruction of transparent optical material as destruction by absorbing inclusions, avalanche ionization, etc.

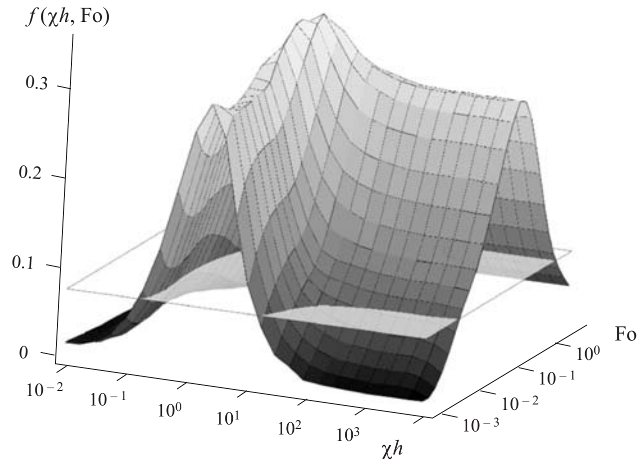

Fig. 1. The graphic solution of inequality (7) for glass K8.

Let us analyze relationship (7). The left side of inequality (7) is a constant characterizing the ratio of the tensile stresses of the material of the plate freely fixed along its contour to the maximum tensile stresses in this plate under one-sided heating. The first part of the inequality is the function of two dimensionless parameters χh and Fo. Figure 1 shows by way of example a graphic solution of inequality (7) for a plate made of optical glass K8.

The function $f(\chi h, \mathrm{Fo})$ reaches its maximum value equal to 0.35 at $\chi h \approx 5$ and $\mathrm{Fo} \approx 0.1$. With $\chi h \to \infty$ the function $f(\chi h, \mathrm{Fo})$ with an accuracy of 0.4% coincides with the function $f(\mathrm{Fo})$ calculated for the case of surface absorption of radiation in [6].

The properties of the material in Fig. 1 are represented in the form of a secant plane. It can be seen that the range of thermoelastic destruction of the plate depends in a complicated manner on the combination of values χh and Fo. With $\mathrm{Fo} > 2$ the destruction of the plate by thermoelastic stresses is impossible for any values of χh. Similarly, at $\chi h < 0.2$, the destruction of the plate by thermoelastic stresses is impossible with any values of Fo. The energy-effective mode is the regime of treatment with small values of Fo and large values of χh. For instance, the thermal strength criterion for glass K8 is satisfied at $\mathrm{Fo} < 5 \times 10^{-3}$ and $\chi h > 15$. The treatment regime with low values χh is not energy-efficient, since high energy density is required. If inequality (7) is satisfied, the temperature of the irradiated plate surface reaches the melting point with a lower energy density than that needed for the plate to be destroyed by thermoelastic stresses. For quartz glasses KI, KV, and KU the left side of inequality (7) is equal to 0.83, and a range of destruction of the plate by thermoelastic stresses does not exist.

Below we list the properties of some optical materials whose initial data are taken from [8 – 11] and GOST 9411–90.

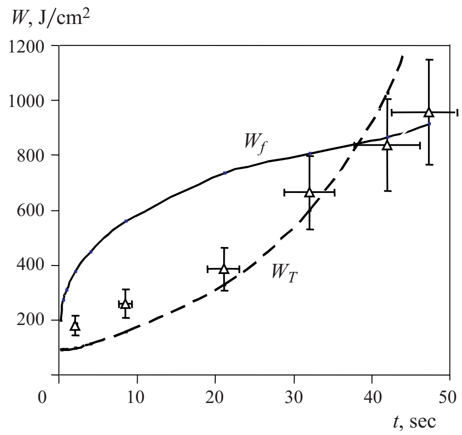

Fig. 2. Dependence of the energy density required for the destruction of samples on exposure duration: △) experimental data.

Material	Criterion of thermal strength of plate (7)
Glass:	
LK3	0.084
K8	0.070
TF1	0.065
TK12	0.063
Ceramics:	
KO3	0.065
KO4	0.012
KO6	1.130
Quartz glasses	0.830

It can be seen that a range of thermoelastic destruction exists for the materials considered (except for optical ceramics KO6 and quartz glasses) under one-sided heating using a volume source.

It should be noted that a calculation based on the analytical relationships produces an error to the amount of the radiation loss. For instance, for glass K8 with a melting point of around 1400 K the maximum radiation loss at the end of the radiation will reach approximately 18 W/cm^2.

To verify the adequacy of the model proposed, the effect of radiation of an LTN-103 laser with a wavelength of 1.06 μm on freely fixed plates of tinted optical glass ZhZS-12 of thickness 0.5 and diameter 1.2 cm was experimentally tested. The absorption index of glass ZhZS-12 for the specified wavelength is 10 cm^{-1} (GOST 9411–90). The laser radiation power is 120 W. The investigated samples were completely covered by the radiation.

The parameters measured included the power of laser radiation measured by a IMO-2N laser power meter, the beam diameter in the plane of the sample, and the time from the beginning of the effect up to the destruction of the sample by thermoelastic stresses or melting of its surface. The measured values were used to calculate the energy density required to destroy samples. Each experimental point was obtained by statistical processing of ten experiments.

The calculation results based on relationships (5) and (6) and the experimental data are shown in Fig. 2. The initial data for the calculation are taken from [8 – 11] and GOST 9411–90. Destruction of the samples by thermoelastic stresses was observed with an exposure duration equal to 32 sec and less when the thermal strength criterion was not satisfied. When the thermal strength criterion was satisfied, melting of the sample surface was observed with an exposure duration over 38 sec. The experimental values of the energy density required to destroy the samples exceed the calculated values by 15 – 20%, which corresponds to radiation losses.

In can be seen from Fig. 2 that increasing the duration of radiation increases the energy density required to reach the melting temperature on the plate surface. When the exposure duration is decreased the criterion of thermal strength is not satisfied. The destruction of the plate by thermoelastic stresses occurs at a lower energy density than that required for the plate surface to reach the melting point. Consequently, to reduce energy consumption, one should select a laser with another wavelength to ensure that the thermal strength criterion is satisfied.

Thus, an analytical relationship has been obtained, which is the criterion of thermoelasticity for a plate freely fixed along its contour under one-side radiation by a volume source and which makes it possible to determine nondestructive regimes of laser treatment of glass and ceramic surfaces and the thermal strength of existing and newly developed materials.

The adequacy of the calculation model has been experimentally verified.

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